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Pseudo-Goldstone Bosons in Technicolor Models and the Phenomenology. *

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Abstract

In this report we present a review of recent developments in the TC/ETC theories, concentrating on the theoretical estimations and the phenomenological analysis about the Non-Oblique corrections on the $Zb\bar{b}$ vertex from ETC dynamics and Pseudo-Goldstone Bosons. The relevant studies about the vertex corrections on other processes from the PGBs were also considered.

Contents

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1 Introduction

After the discovery of top quark and the measurement of its mass at Fermilab [1, 2] the investigation for the mechanism of the electroweak symmetry breaking(ESB) becomes the number one task facing particle physics society. At present there is no any evidence to show which mechanism is responsible for the ESB. The fundamental Higgs boson, which is responsible for the spontaneous symmetry breaking in the Standard Model(SM) [3], has not been discovered so far despite the intensive searching in experiments. This lack of experimental observation of the elementary Higgs boson is one of the main motivations for constructing models of dynamical electroweak symmetry breaking(DESB).

Since last Spring, it has been widely reported that there is a discrepancy between the measured R_b, $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to hadrons)$, at LEP and the theoretical prediction of the SM:

$$\begin{aligned} R_b^{exp} &= 0.2202 \pm 0.0020, \ (1994, \text{ ref.}[4]) \\ &= 0.2204 \pm 0.0020, \ (1995, \text{ ref.}[5]), \end{aligned} \tag{1}$$

while in the SM,

$$R_b^{SM} = 0.2158 \pm 0.0004 \quad for \quad m_t = 180 \pm 12\, GeV \tag{2}$$

It is easy to see that the R_b^{SM} is approximately $2-\sigma$ away from the measured R_b. A positive contribution to R_b from new physics clearly is required to lift the R_b to the measured value. Of cause we understand that the size of measured R_b may decrease along with the progress of the experiments [6]. However, if the observed deviation is really the long-awaited deviation from the SM, its implication for those new theories beyond standard model are very interesting.

In theories of DESB, such as technicolor(TC) [7], electroweak symmetry breaking is due to chiral symmetry breaking in an asymptotically-free, strongly-interacting, gauge theory with massless fermions. Technicolor and extended technicolor (ETC) [7, 8, 9] theories generally yield large effects on the physical observables. A common approach to studying the new physics effects is to assume that the dominant effect comes from oblique corrections, which have been conveniently parametrized in terms of three parameters S, T and U [10] or ϵ_1, ϵ_2, ϵ_3 and ϵ_b [11]. More recently, the (S, T, U) parametrization has been extended by introduction of additional three parameters (V, W, X) [12, 13, 14].

In general, contributions from vertex and box diagrams are usually tiny. But for the $Zb\bar{b}$ vertex, the situation is changed greatly [15, 16]. In fact, the non-oblique corrections on the $Zb\bar{b}$ vertex from the sideways and diagonal ETC gauge boson exchanges [17, 18, 19, 20, 21], as well as from the charged Pseudo-Goldstone bosons (PGBs) exchanges [22, 23] could be rather large, which will affect the partial decay width $\Gamma_b = \Gamma(Z \to b\bar{b})$ and consequently the ratio R_b and other relevant observables. The systematic studies about non-oblique corrections on the $Zb\bar{b}$ vertex are very interesting for one to look for the new physics effects on precisely measured observables.

In a previous review paper [24], S.F.King has described a general picture of the basic structures and recent developments of dynamical electroweak symmetry breaking. In this report we concentrate on the studies about the non-oblique corrections on the $Zb\bar{b}$ vertex from ETC gauge boson exchanges (sideways and diagonal) and from the charged PGBs, and to see that what

implications are there for TC/ETC theories, if the true values of m_t, R_b and other relevant observables are within their reported $1-\sigma$ error.

This paper is organized as follows: In section 2 we first list the new data reported at the 1995 Winter conference[5], and then present the theoretical predictions for R_b and other observables in the SM. Discussions about the particle spectrum of simple TC/ETC models and possible experimental signatures are condensed into the section 3. The original ideas and recent developments about the parametrization of oblique corrections in TC theory are presented in section 4. In section 5 we discuss the non-oblique corrections on the $Zb\bar{b}$ vertex form various sources, especially from the exchanges of charged PGBs which appeared in the QCD-like one-generation TC model(OGTM) [8]. In section 6 we briefly discuss and comment on several new TC models proposed very recently in the sense of avoiding the existed constraints imposed by the precision data. The conclusions are also included in section 6.

2 The $Zb\bar{b}$ vertex in Standard Model

With LEP entering into its final period of measurements on the Z peak, the accuracy achieved in LEP experiments now reaches a very high level, as illustrated in Table 1 [5, 25]. The current precision achieved at LEP (Moriond 1995) [5] and at SLC experiments now permits very rigorous tests of the SM and encourage us to study possible discrepancies between experiments and SM predictions. While the SM is generally in excellent agreement with experiment, recent results on the left-right asymmetry A_{LR} at SLC [26] and the ratio R_b measured at LEP [4, 5] indicate a possible disagreement at 2 to 2.5σ level. The values of strong coupling constant α_s, measured at the low-energy experiments and at the M_Z scale respectively, also show some disagreement.

Table 1: The experimental values for the precision Z-pole observables, directly quoted from ref.(25)

Quantity	experimental Value	Standard Model Fit
M_Z (GeV)	91.1887 ± 0.0022	input
Γ_Z (GeV)	2.4971 ± 0.0033	2.4979
σ_p^h (nb)	41.492 ± 0.081	41.441
$R_e = \Gamma_h/\Gamma_e$	20.843 ± 0.060	20.783
$R_\mu = \Gamma_h/\Gamma_\mu$	20.805 ± 0.048	20.783
$R_\tau = \Gamma_h/\Gamma_\tau$	20.798 ± 0.066	20.783
$A_{FB}^0(e)$	0.0154 ± 0.0030	0.0157
$A_{FB}^0(\mu)$	0.0160 ± 0.0017	0.0157
$A_{FB}^0(\tau)$	0.0209 ± 0.0024	0.0157
$A_\tau(P_\tau)$	0.140 ± 0.008	0.145
$A_e(P_\tau)$	0.137 ± 0.009	0.145
R_b	0.2204 ± 0.0020	0.2157
R_c	0.1606 ± 0.0095	0.172
$A_{FB}^0(b)$	0.1015 ± 0.0036	0.1015
$A_{FB}^0(c)$	0.0760 ± 0.0089	0.0724
A_{LR}^0	0.1637 ± 0.0075	0.145

In this report we concentrated on the investigations about the ratio R_b, for relevant studies

of other two observables the reader can see the refs.[27, 28]

2.1 The top quark and Higgs boson

In last Spring, the CDF collaboration first published [29] the evidence for the existence of the top quark. In this March, the CDF [1] and D0 [2] collaborations at Fermilab announced the observation of top quark in $p\overline{p}$ collisions at the Tevatron. Both groups saw a statistically significant excess of dilepton and lepton + jet events with the proper kinematic properties and bottom quark tags needed to indicate $t\overline{t}$ production. Furthermore, they were able to extract mass values of top quark by fitting to events consisting of a single lepton plus four jets. The CDF group found that $m_t = 176 \pm 8 \pm 10\ GeV$ [1], while D0 Collaboration obtained a mass of $m_t = 199^{+19}_{-21} \pm 22\ GeV$ [2], and the weighted average is $m_t = 180 \pm 12\ GeV$. The measured top quark mass is in very good agreement with the prediction based on the SM electroweak fits of the LEP and other data, $m_t = 178 \pm 11^{+18}_{-19}\ GeV$ [4], where the central value and the first error refer to $M_H = 300\ GeV$. This measurement of m_t, while still not very precise, should help in reducing the present uncertainties on almost all electroweak observables. The direct observation of the top quark at the Tevatron heralds the start of a new era in the study of particle physics.

The top quark is certainly unique among the ordinary fermions. It is the heaviest fermion discovered so far, more than 30 times as massive as the bottom quark. Correspondingly, top quark has the largest coupling to the symmetry breaking sector of all the known particles. This large coupling to the Higgs sector may give rise to deviations from its expected behavior, thereby offering clues to electroweak symmetry breaking, fermion mass generation, quark family replication, and other deficiencies of the standard model. Obviously, the knowledge of m_t will be very helpful for one to look for the hints of new physics. According to current estimation the combined CDF+D0 determination of m_t could provide an overall error $\Delta m_t = \pm 3\ GeV$ [30] by the end of this century. It will probably be necessary to wait for an NLC to get m_t with an accuracy of less than 1 GeV [31]. For a general discussion of top quark physics one can see the paper written by C.P.Yuan [32].

After the discovery of the top quark and the measurement of its mass the main uncertainties of the SM expectations for those observables are clearly due to our ignorance about the Higgs boson mass. Theoretically, Higgs boson mass is a free parameter of the SM. If Higgs bosons exist as discernible states, theoretical consistency demands that they lie below about $700-800\ GeV$. The current lower limit is $M_H > 63\ GeV$ [33], which is coming from the failer of the direct searches at LEP. The LEP 200 can rise this limit to about 90 GeV. On the other hand, the steadily increasing accuracy of the data starts to exhibit some weak sensitivity to the Higgs boson mass [34]. As described in ref.[35] the χ^2 distribution generally predicts a light Higgs boson. However, the constraint is weak statistically. From the χ^2 distribution one can obtains the weak upper limits [35]

$$M_H < 510(730)\ GeV \quad \text{at } 90(95)\%\text{C.L}, \tag{3}$$

from the indirect precision data and the CDF measurement of m_t (where $m_t = 174 \pm 16\ GeV$ was used). This sensitivity to the M_H is driven almost entirely by the measured R_b and A^0_{LR}, both of which are well above the corresponding SM expectations. Omitting these two data leads to an almost flat χ^2 distribution, as illustrated in Fig.11 of ref.[35]. If the present deviations of R_b and A^0_{LR} are due to large statistical fluctuations or new physics beyond the SM the above upper constraints on M_H will disappear.

Although some researchers claim that the current data prefer a relatively light Higgs boson [34], but in fact there is no definite constraint on M_H existed now. A recent analysis done by

M.Consoli and Z.Hoiki [36] using the data from the 1995 Winter conference suggest that the Higgs boson mass should be in the heavy range, say, $M_H \sim 500 - 1000\ GeV$ for $m_t = 180\ GeV$. This result is in agreement with the indications from the Δr (*e.g.*, M_W) analysis [37].

Further improvement in the data taking is needed for a definite answer to the value of M_H. Consequently, it is dangerous to focus on a light-mass region in Higgs searches at future experiments. According to the studies in refs.[36, 38] it is possible to obtain precious information on the Higgs mass when the top quark mass will be measured with a high precision.

2.2 Non-oblique corrections on the $Zb\bar{b}$ vertex in SM

For LEP processes there are two types of radiative corrections: the corrections to the gauge boson self-energies and the corrections to the $Zb\bar{b}$ vertex. In the evaluation of self-energy corrections the error due to our ignorance of the Higgs mass is substantial after the direct measurement of m_t at Fermilab [1, 2]. On the other hand, in the corrections to the $Zb\bar{b}$ vertex, where the leading contribution due to the large top quark mass is produced by the exchange of the W bosons, there is no dependence on the unknown Higgs mass. Moreover, the possible new physics contributions to the $Zb\bar{b}$ vertex are much more restricted. Any non-standard behavior most possibly means the existence of new physics!

The observables (which are in close relation with the $Zb\bar{b}$ vertex) considered in this paper include Γ_b, Γ_h, Γ_Z, R_b, R_c and R_l, they are well determined theoretically and experimentally. Because the asymmetry A^b_{FB} is almost unaffected by the $Zb\bar{b}$ vertex correction [11] we will not include this quantity in our analysis.

In the framework of standard model calculations of the one-loop corrections to the $Zb\bar{b}$ vertex has been performed by several groups [40]. The partial decay width $\Gamma(Z \to f\overline{f})$ has been calculated in the $\overline{MS}$ renormalization scheme [41] and has been expressed in a compact form [42],

$$\begin{aligned}\Gamma(Z \to f\overline{f}) &= \frac{N_c^f}{48}\frac{\hat{\alpha}}{\hat{s}_w^2\hat{c}_w^2}\, m_Z[\hat{a}_f^2 + \hat{v}_f^2](1+\delta_f^{(0)})(1+\delta_{QED}^f) \\ &\quad \cdot(1+\delta_{QCD})(1+\delta_\mu^f)(1+\delta_{tQCD}^f)(1+\delta_b), \end{aligned} \tag{4}$$

where $N_c^f = 3(1)$ for quarks (leptons) is the color factor, $\hat{\alpha}$ is the electromagnetic coupling constant defined at the M_Z scale, $\hat{s}_w^2$ is the Weinberg angle in the $\overline{MS}$ scheme, and the $\hat{v}_f$ and $\hat{a}_f$ are the effective vector and axial coupling constants of the Z boson to the fermions. The partial decay widths in eq.(4) has included the genuine electroweak corrections, the QED and QCD corrections, as well as the corrections to $Zb\bar{b}$ vertex due to the large top quark mass. The definitions and the explicit expressions for all functions and factors appeared in eq.(4) can be found in refs.[41, 42]. In ref.[43], J.Fleischer *et al* calculated the two-loop $0(\alpha\alpha_s)$ QCD corrections to the partial decay width Γ_b, and they found a screening of the leading one-loop top mass effects by $m_t \to m_t\,[1 - \frac{1}{3}(\pi^2 - 3)\alpha_s/\pi]$. The expression for $\Gamma(Z \to f\bar{f})$ in eq.(4) is very convenient for the calculation of branching ratios because most factors will be canceled in the ratios of widths. For more details about the calculations of Γ_i and other relevant quantities in the SM one can see the refs.[40, 41] and a more recent paper [16].

In our analysis, the measured values [1, 2, 4, 5, 44, 45] $m_Z = 91.1887 \pm 0.0022\ GeV$, $G_\mu = 1.16639 \times 10^{-5}(GeV)^{-2}$, $\alpha^{-1} = 137.0359895$, $\alpha_s(m_Z) = 0.125 \pm 0.005$, $m_e = 0.511\ MeV$, $m_\mu = 105.6584\ MeV$ and $m_\tau = 1776.9\ MeV$, together with $m_t = 180 \pm 12\ GeV$ and the assumed value $M_H = 300^{+700}_{-240}\ GeV$ are used as the input parameters. In the numerical calculations we conservatively take the "on-shell" mass of the b-quark the value $m_b = 4.6 \pm 0.3\ GeV$ (in ref.[42],

the authors used $m_b = 4.6 \pm 0.1\ GeV$), and use the known relation [46] between the "on-shell" and the $\overline{MS}$ schemes to compute the running mass $\overline{m_b}(m_Z)$ at the Z scale. We also use the same treatment for the c-quark and take $m_c = 1.5\,GeV$ as its "on-shell" mass. For other three light quarks we simply assume that $\overline{m_i}(m_Z) = 0.1\,GeV$ $(i = u, d, s)$. All these input parameters will be referred to as the *Standard Input Parameters* (SIP).

Using the SIP, the SM predictions for Z decay widths and the ratios can be calculated easily. The size of uncertainties in Γ_i and R_j depend on the errors of m_t, M_H. $\overline{m_b}(M_Z)$, $\alpha_s(M_Z)$ and $\hat{\alpha}$. For instance, the partial decay width Γ_b and the ratio R_j (j=b, c, l) can be written in the following form:

$$\begin{aligned}
\Gamma_b &= 377.8 \pm 0.2(m_t)^{-0.9}_{+0.2}(M_H) \pm 0.5(\alpha_s) \pm 0.4(\hat{\alpha}) && (5)\\
R_b &= 0.2158 \pm 0.0004(m_t) \pm 0.00003(M_H) \pm 0.00004(\alpha_s) \pm 0.0001(\overline{m_b}) && (6)\\
R_c &= 0.1722\ \pm 0.0002(m_t)\ \pm 0.00004(M_H) \pm 0.0001(\alpha_s) \pm 0.00003(\overline{m_b}) && (7)\\
R_l &= 20.820 \pm 0.002(m_t)^{-0.015}_{+0.011}(M_H) \pm 0.034(\alpha_s) \pm 0.003(\overline{m_b}) && (8)
\end{aligned}$$

where the central value corresponds to $m_t = 180\ GeV$, $M_H = 300\ GeV$, $\alpha_s(M_Z) = 0.125$ and $\overline{m_b}(M_Z) = 2.8\ GeV$. The contributions to the Z boson decay width from the $0(\alpha^2)$ terms are less than 0.1 MeV and can be neglected completely.

Among the electroweak observables the ratio R_b is the special one [16]. For this ratio most of the vacuum polarization corrections depending on the m_t and M_H cancel out, while the experimental uncertainties in the detector response to hadronic events also basically cancel. Furthermore, this ratio is also insensitive to extensions of the SM which would only contribute to vacuum polarizations. Analytically, the ratio R_b has a complicated dependence on the m_t and M_H in the region under study ($m_t = 180 \pm 12\ GeV$, $M_H = 60 \sim 1000\ GeV$). Its plot is shown in Fig.1. The two parameter (m_t and M_H) fitting to the exact results gives

$$R_b^{SM} = 0.21892 - 10^{-4} \cdot \left[7.45 \frac{m_t^2}{m_Z^2} + 1.75 \ln\left[\frac{m_t^2}{m_Z^2}\right] - 0.098 \ln\left[\frac{M_H^2}{m_Z^2}\right]\right]. \tag{9}$$

The errors introduced with this parametrization in the region under study is completely negligible (less than 0.00001)

For the ratio R_c, the current accuracy of the data is limited by systematic effects, coming from the large bottom contamination in the charm samples [47]. The new LEP value $R_c = 0.1606 \pm 0.0095$ is in good agreement with the SM prediction although the error of the data is still large.

The current accuracy of the ratio R_l is very high, $R_l = 20.820 \pm 0.035$ [1], the relative error is about 0.17%. In SM, the R_l is practically a constant for given m_Z due to (accidental) cancellations between the universal and vertex contributions. Non-standard terms would spoil this cancellation and exhibit a deviation from the SM value. However, the present data does not show deviations from the SM.

For the ratio R_b, the situation is more interesting:

- The direct measurement of m_t at CDF and D0, $m_t = 180 \pm 12\ GeV$, while still not very precise, has provided a great help in reducing the theoretical uncertainty of R_b to 0.0004.
- The two-loop $0(\alpha\alpha_s)$ QCD contribute a 0.0006 positive correction to the central value of R_b. As illustrated in Fig.1, where the lower curve with solid triangle symbols shows the R_b at one-loop level and the upper line with solid square symbols represents the R_b with the inclusion

[1] $R_l = 20.820 \pm 0.035$ is the weighted average of the measured R_e, R_μ and R_τ as given in Table 1.

of $0(\alpha\alpha_s)$ QCD corrections, the two-loop QCD contribution makes the R_b moving in the right direction toward the range preferred by the data.

- From the Fig.1, it is easy to see that the R_b is about two standard deviations away from the central value of the measured R_b. The deviation reaches 2.2-σ (or 2.5-σ at one-loop order) for $m_t = 180\ GeV$.

Because of special vertex corrections, the partial width Γ_b actually decreases with m_t, as opposed to the other widths which will increase. The ratio R_b is insensitive to the still unknown Higgs boson mass M_H. However, when combined with other observables, for which m_t and M_H are strongly correlated, the effect is to favor a smaller Higgs mass, as discussed previously. If the current deviation of R_b is more than a statistical fluctuation, it must be due to some sort of new physics. We know that many types of new physics, such as the TC/ETC theories, will couple preferentially to the 3rd generation, so the careful investigations about the possible contributions to the $Zb\bar{b}$ vertex form the new physics are certainly very important !

2.3 The vertex factor Δ_b^{new}

The precision data can be used to set limits on TC theory as well as other kinds of new physics. Besides the m_t dependence the $Zb\bar{b}$ vertex is also sensitive to a number of types of new physics. One can parametrize such effects by [35]

$$\Gamma_b = \Gamma_b^{SM}(1 + \Delta_b^{new}) \tag{10}$$

where the term Δ_b^{new} represents the pure non-oblique corrections to the $Zb\bar{b}$ vertex from new physics, while the oblique corrections to Γ_b have been neglected. The partial decay width Γ_b^{SM} can be determined theoretically by eq.(4), and other five observables ($\Gamma_h,\ \Gamma_Z,\ R_b,\ R_c,\ R_l$) can be written in a general form

$$O_i = O_i^{SM} + \lambda_i \cdot \Delta_b^{new} + \sum_{j=1}^{6} C_{ij} \cdot P_j, \tag{11}$$

Where P_j represent oblique parameters (S, T, U, V, W, X), and C_{ij} are the corresponding coefficients respectively.

The parameter W appears in the decay width of the W boson, but not in the precision electroweak observables studied here. Concerning X, explicit calculations in ETC models [12, 13, 14] find that the X parameter is very small in all scenarios, so it can also be neglected in our studies about the $Zb\bar{b}$ vertex. The parameter V may become significant for small technifermion masses [14] $M_{N,E,U,D} \leq M_Z$. However, following J.Ellis's argument, we also regard this possibility as unlikely. According to recent studies [35] the parameters (S, T, U) are all close to zero with small errors. On the other hand, the oblique corrections will be basically canceled in the ratios (R_b, R_c, R_l), the corresponding coefficients should be very small. In short, since we here concentrate on estimating the non-oblique corrections on the $Zb\bar{b}$ vertex from new physics and studying its implications for TC/ETC theories, we could neglect all those six oblique parameters approximately (*e.g.*, we do one-parameter fit).

The definition of Δ_b^{new} in eq.(10) is different from that of ϵ_b [11](as well as the parameter Δ_b in refs.[48, 15]), and this vertex factor Δ_{bv}^{new} represents the pure non-oblique corrections on the $Zb\bar{b}$ vertex.

In a previous paper [49] we used the likelihood function method to derive out the value of Δ_{bv}^{new} from the data set $(\Gamma_b, \Gamma_h, \Gamma_Z, R_b, R_c, R_l)$. With the SIP, the point which maximizes

$\mathcal{L}(x_{exp}, \Delta_b^{new})$ is found to be [49]

$$\Delta_b^{new} = 0.017 \pm 0.007 \quad at \quad 68\% C.L., \quad (\text{only } \Gamma_b \text{ and } R_b \text{ included}), \tag{12}$$

$$= 0 \pm 0.005 \quad at \quad 68\% C.L., \quad (\text{all six observables included}), \tag{13}$$

for $m_t = 180\ GeV$ and $M_H = 300\ GeV$. One can also obtain the 95% one-sided upper (lower) confidence limits on Δ_b^{new}:

$$-0.011 < \Delta_{b,exp}^{new} < 0.011, \quad (\text{all six observables included}) \tag{14}$$

for $m_t = 180 \pm 12\ GeV$ and $60\ GeV \leq M_H \leq 1000\ GeV$.

In the following analysis we will use the $\Delta_{b,exp}^{new}$ as the experimentally determined vertex factor.

3 Pseudo-Goldstone bosons in TC models

The subject of dynamical electroweak symmetry breaking (DESB) has a long and distinguished history going back to the early work of Nambu and Jona-Lasinio [50]). A series of pioneering papers followed which extended these ideas to the realm of gauge theories. Eventually the idea of technicolor (TC) was introduced by Susskind and Weinberg [7] as a mechanism for DESB. The early development of TC is nicely traced in the collection or reprints by Farhi and Jackiw [51].

TC theory is modeled on the known behavior of quarks in QCD – but scaled up to the TeV scale. It turns out that TC by itself is not sufficient to provide fermion masses. One way forward is to embed the TC gauge group into a larger gauge group known as ETC. However we shall see it is not an easy task to describe the quark and lepton mass spectrum without running into phenomenological problems. These problems include the flavor-changing neutral current (FCNC) problem, problems of producing the correct spectrum for ordinary fermions, specifically the heavy top quark mass. These problems have thwarted attempts to construct ETC models, and to date there is no accepted standard ETC model in the literature. Recently ETC has staged a comeback due to a lot of exciting progress with the above problems. Such as the invention of ideas of "Walking TC" [52] and "Strong ETC" [53]. Both these ideas result in the technifermion T condensate receiving a high momentum enhancement, while the pion decay constants F_π which depend on low momentum physics are almost unchanged. This is important since the quark and lepton masses and PGB masses depend upon the value of the condensate, while the W, Z masses depend upon F_π. Condensate enhancement may therefore increase fermion masses without increasing gauge boson masses.

In this section we focus on the studies about the spectrum of pseudo-Goldstone bosons in the OGTM. For recent progress of TC and ETC theories, the reader can also see the review papers written by Lane [54], King[24], and by Chivukula *et al* [55].

3.1 PGBs in the OGTM

In this section we consider the single techni-family scenario, and briefly discuss the resulting pseudo-Goldstone boson phenomenology. Consider a TC model based on the gauge group,

$$SU(N)_{TC} \otimes SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \tag{15}$$

and with a single techni-family,

$$
\begin{array}{lcl}
Q_L{}^\alpha = \begin{pmatrix} U_L \\ D_L \end{pmatrix}^\alpha & \sim & (N,3,2,1/6) \\
U_R{}^\alpha & \sim & (N,3,1,2/3) \\
D_R{}^\alpha & \sim & (N,3,1,-1/3) \\
L_L{}^\alpha = \begin{pmatrix} N_L \\ E_L \end{pmatrix}^\alpha & \sim & (N,1,2,-1/2) \\
E_R{}^\alpha & \sim & (N,1,1,1) \\
N_R{}^\alpha & \sim & (N,1,1,0)
\end{array}
\tag{16}
$$

where $\alpha = 1 \ldots N$ is the G_{TC} index. The technifermions which carry technicolor and QCD color are referred to as techniquarks, while the technifermions which carry technicolor but not QCD color are called technileptons. Note that the right-handed technineutrino N_R is required by anomaly cancellation, and cannot be given a Majorana mass without breaking $SU(N)_{TC}$. The ordinary quarks and leptons transform as usual and are technicolor singlets. In the limit that QCD and electroweak interactions are switched off, the TC sector of the model respects a large chiral symmetry $SU(8)_L \otimes SU(8)_R$. Electroweak symmetry is broken by the condensate $< \overline{T}T > \neq 0$. Since the techniquark condensates have QCD color, there are really eight separate condensates above, which break the chiral symmetry down to $SU(8)_{L+R}$. The electroweak symmetry is now broken by the equivalent of four separate technidoublets (e.g., $N_D = 4$) and thus the gauge boson masses are given by

$$
M_W = \frac{1}{2} g(\sqrt{4}F_\pi), \quad M_Z = \frac{g\sqrt{4}F_\pi}{2\cos_{\theta_w}}, \tag{17}
$$

and the technipion decay constant mass is now,

$$
F_\pi = \frac{246}{\sqrt{4}} GeV = 123 GeV \tag{18}
$$

According to Goldstone's theorem we would expect $8^2 - 1 = 63$ massless (Pseudo)-Goldstone bosons produced from this breaking, one for each broken generator. Three of them are eaten by the Higgs mechanism, while the remainder are assumed to get masses from a combination of color, electroweak gauge interactions and ETC interactions.

The 60 PGBs of the $SU(N)_{TC}$ model consist of the following states,

$$
\begin{array}{lcl}
P_8^\pm & \sim & \overline{Q}\gamma_5\lambda_\alpha\tau^1 Q \pm i\overline{Q}\gamma_5\lambda_\alpha\tau^2 Q \\
P_8^0 & \sim & \overline{Q}\gamma_5\lambda_\alpha\tau^3 Q \ , \quad P_8^{0'} \sim \overline{Q}\gamma_5\lambda_\alpha Q \\
T_i^a & \sim & \overline{Q_i}\gamma_5\tau^a L, \quad T_i \sim \overline{Q_i}\gamma_5 L \\
\overline{T}_i^a & \sim & \overline{L}\gamma_5\tau^a Q_i, \quad \overline{T}_i \sim \overline{L}\gamma_5 Q_i \\
P^\pm & \sim & \overline{Q}\gamma_5\tau^\pm Q - 3\overline{L}\gamma_5\tau^\pm L \\
P^0 & \sim & \overline{Q}\gamma_5\tau^3 Q - 3\overline{L}\gamma_5\tau^3 L \ , \quad P^{0'} \sim \overline{Q}\gamma_5 Q - 3\overline{L}\gamma_5 L
\end{array}
\tag{19}
$$

where $Q = (U,D)$, $L = (N,E)$, λ^α ($\alpha = 1 \ldots 8$) are the Gell-Mann color matrices and τ^a ($a = 1 \ldots 3$) are the Pauli isospin matrices. These 60 PGBs can be classified as follows:

- The four color octets, which form an isotriplet, $P_8^\pm$ with charges ± 1 and P_8^0, and an isosinglet, $P_8^{0'}$.

- Four color triplets and four color anti-triplets, which form one isotriplet T_i^a and its self-conjugate $\overline{T}_i^a$, and isosinglet T_i and its conjugate $\overline{T}_i$. They are composites made out of a techniquark and a technilepton or *vice versa*. We usually refer to them as leptonquark PGBs.
- Four color singlet, which also form a triplet ($P^{\pm}$ and P^0) and singlet $P^{0'}$ of isospin.

In the OGTM, besides the presence of PGBs, the vector resonances (ρ_T's and ω_T) will also appear. All these particles may be classified by their $SU(3)_c$ and $SU(2)_V$ quantum numbers as shown in Table 2.

Table 2: Spectrum of particles in non-minimal technicolor models.

$SU(3)_C$	$SU(2)_V$	PGBs	V-resonances
1	1	$P^{0\prime}$	ω_T
1	3	$P^{0,\pm}$	$\rho_T^{0,\pm}$
3	1	$P_3^{0\prime}$	$\rho_{T3}^{0\prime}$
3	3	$P_3^{0,\pm}$	$\rho_{T3}^{0,\pm}$
8	1	$P_8^{0\prime}(\eta_T)$	$\rho_{T8}^{0\prime}$
8	3	$P_8^{0,\pm}$	$\rho_{T8}^{0,\pm}$

3.2 Estimation for the Masses of PGBs

There are several kinds of contributions to the masses of PGBs: electroweak interactions, QCD interactions, and ETC interactions. Peskin and Preskill [56] have calculated the contributions to the PGB masses due to the color and electroweak interactions. The ETC contribution to these masses have been worked out by Binétruy *et al* [57].

In the limit where standard model interactions and ETC interactions are turned off, the PGBs would be massless. Turning on gauge interactions causes the PGBs to receive mass contributions from graphs with a single gauge boson exchange. At first the electroweak contributions to the masses of PGBs are theoretically well understood and can be reliably computed (with some dependence on the TC model) [56]:

$$M_{P^{\pm}}|_{EW} \approx 5 - 14\, GeV. \tag{20}$$

For colored PGBs the QCD contributions to their mass will be dominant. For $SU(N_{TC})$ TC models with QCD-like dynamics one can estimate the QCD contributions to the colored PGBs [56]:

$$M^2|_{QCD} = 3\alpha_s M_{TC}^2 \approx 3\alpha_s \left[\frac{8F_\pi}{\sqrt{N_{TC}}}\right]^2. \tag{21}$$

where $F_\pi = 246/\sqrt{N_D}\, GeV$ is the TC analog of the QCD f_π.

With the inclusion of electroweak and QCD contributions one can obtains the masses of PGBs in the SU scenario as follows [56]:

$$\begin{aligned} Color\ \ singlets,\ \ P^{\pm}, P^0, P^{0\prime} \quad & \sim 10\, GeV \\ Color\ \ triplets, \quad & 160 - 170\sqrt{4/N_{TC}}\, GeV \\ Color\ \ octets,\ \ P_8^{\pm}, P_8^0, P_8^{0\prime} \quad & 246\sqrt{4/N_{TC}}\, GeV \end{aligned} \tag{22}$$

These masses could be increased in walking TC theories since the condensate enhancement also enhances PGB masses. We also expect additional uncertainties for models (multiscale, strong ETC) where the TC dynamics is quite different from QCD.

Finally, turning on the ETC interactions can give rise to masses for the PGBs. Although the ETC contributions to the PGB masses are entirely model dependent, one expects, based on Dashen's formula [58], that these contributions have the following form [55]:

$$M_P^2|_{ETC} \approx \frac{<\overline{\Psi}\Psi\overline{\Psi}\Psi>}{F_\pi^2\Lambda_f^2}, \tag{23}$$

where Ψ is the technifermion field, and $\Lambda_f \equiv M_{ETC}/g_{ETC}$ is the ETC scale associated with an ordinary fermion f. Assuming that the vev of the four-fermion operator factorizes, one have:

$$M_P|_{ETC} \approx \frac{<\overline{\Psi}\Psi>}{F\Lambda_f} \approx \frac{m_f}{F}\,\Lambda_f. \tag{24}$$

Further more, if there exists a consistent dynamical model of EWSB which can produce a heavy enough t quark, then using a t quark mass of 180 GeV, F_π of 123 GeV, and an ETC scale at least as large as the technicolor scale of a TeV, we have a contribution to the PGB mass of the order of 1 TeV! Thus it may not be surprising if PGBs are not found at colliders any time soon. Consequently, the masses of PGBs will be considered as "free" parameters in the following phenomenological analysis.

3.3 Possible experimental signatures of PGBs

The experimental signatures of the PGBs were studied by Ellis *et al* [59], Dimopoulos [60], and Eichten *et al* [61]. Very recently, Chivukula *et al* [55] presented a long report to summarize the possible signatures of colored PGBs and resonances at existing and proposal colliders.

We here only provide a scanning of possible experimental signatures of the PGBs. For more details see the papers mentioned above.

It is relatively straightforward to find the color octet PGBs at the LHC, but much harder (but not impossible) at the Tevatron. Consider the color octet neutral state $P_8^{0\prime}$, which is a techni-isospin singlet and can be produced singly in hadronic collisions with a cross-section $d\sigma/dy \approx 1(10^{-2})$ nb at the LHC (Tevatron) (for rapidity $y=0$). The $P_8^{0\prime}$ can decay back into gg or into $t\bar{t}$ if kinematically allowed. The first signal at the Tevatron may be an enhancement of the top quark production cross-section, as discussed by Eichten *et al* [61] and Appelquist and Triantaphyllou [62]. In fact the CDF and D0 cross-section for $t\bar{t}$ production does appear to be slightly higher than standard model expectations [1, 2, 29] [2].

The color triplets are examples of leptonquarks. There are many of them in the spectrum, consisting of color triplet combinations such as $U\overline{N}$, $U\overline{E}$, $D\overline{N}$, $D\overline{E}$ and their antiparticles. At the LHC or HERA they are copiously pair produced and tend to decay into heavy quarks and leptons with relatively background-free signatures. For example a typical signature of a leptonquark pair might be $t\bar{t}\tau\overline{\tau}$ which has a particularly low background. For more details about the productions and decays of leptonquarks the reader can see a new report written by A.Djouadi *et al* [63].

[2] Last year, CDF published the evidence of top quark production with $\sigma_t = 13.9^{+6.1}_{-4.8}$ pb [29]; In this March, both CDF and D0 announced the discovery of top quark with $\sigma_t = 6.8^{+3.6}_{-2.4}$ pb [1], and $\sigma_t = 6.4 \pm 2.2$ pb [2]; while the SM prediction is $\sigma_t^{SM} = 4.5 \pm 0.3$ pb for $m_t \approx 180$ GeV. Although the central value of the measured σ_t is larger than that predicted by the SM, but the measured and theoretically predicted top quark production cross-section are obviously agree within $1-\sigma$ level.

The color singlets are similar to charged and neutral Higgs bosons. The best place to look for them is the clean environment provided by the high energy e^+e^- colliders, although they should also be seen at the LHC. The neutral PGBs do not have a tree-level coupling to the Z boson, however, which should enable it to be distinguished from neutral Higgs bosons. They couple to gauge bosons via the triangle anomaly, with technifermions running round the loop, as discussed in some detail in ref.[59, 55].

In ref.[64], Lubicz and Santorelli estimated the production and decay of neutral PGBs at LEP II and NLC in multiscale walking technicolor (WTC) models. They found that, in Lane-Ramana multiscale model [65], because of the existence of relatively low TC scales, the production of neutral PGBs, in e^+e^- colliders LEP II or NLC, is significantly enhanced. This enhancement is expected to increase the corresponding cross sections by one or two orders of magnitude with respect to the prediction of traditional TC models. The neutral PGBs could be observed mainly in the processes $e^+e^- \to P\gamma$, Pe^+e^- or PZ^0 (if kinematically allowed) at LEP II and at NLC.

The charged PGBs couple to the photon and Z by tree-level couplings which resemble those for charged Higgs, and like charged Higgs tend to decay into the heaviest fermions around. The current lower limit on the mass of charged Higgs bosons is generally equivalent to the lower limit on the mass of color singlet PGBs, *e.g.*, $M(P^{\pm}) > 41.7\ GeV$ at present [66].

Finally note that the colored PGBs may re-scatter into eaten technipions, and hence may enhance the rates of longitudinal gauge boson scattering, as observed by Bagger, Dawson and Valencia [67].

In order to give an overlook for the discovery potential of those PGBs appeared in TC models we present the Table 3 (directly quoted from ref.[55]), which summarize the discovery reach of different machines. For a more general study about the searchers for new particles at existing and proposal high energy colliders one can see ref.[31].

Table 3: Discovery reach of different accelerators for particles associated with realistic models of a strong EWSB sector, the masses in GeV. Directly quoted from ref.(55) with small modification.

Particle	Tevatron	LHC	LEP I	LEP II	TLC
$P^{0\prime}$	—	$110-150$ ^{a}	8 ^{b} ; 28 ^{b}	—^{c}	—^{c}
P^0	—	—	—	—	—
P^+P^-	—	400 ^{d}	41.7 ^{e}	100 ^{f}	500 ^{f}
$P_8^{0\prime}(\eta_T)$	$400-500$ ^{g}	325 ^{h}	—	—	—
P_8^0	$10-20$ ^{h}	325 ^{h,i}	—	—	—
$P_8^+P_8^-$	$10-20$ ^{h,i}	325 ^{h,i}	45 ^{e}	100 ^{f}	500 ^{f}
$P_3^+P_3^-$	—^{i}	—^{i}	—	100 ^{f}	500 ^{f}

^{a} Decay mode $P^{0\prime} \to \gamma\gamma$, similar to a light neutral Higgs [68].

[b] Decay mode $Z \to \gamma P^{0\prime}$, assuming a one-family model, with $N_{TC} = 7$ and $N_{TC} = 8$ respectively; no reach for $N_{TC} < 7$; for larger $Z\gamma P^{0\prime}$ couplings, the discovery reach extends to 65 GeV [69, 70, 71].
[c] No reach for traditional one-family model; possibility of reach for the Lane-Ramana [65] multiscale model in several processes. The discovery reach could be greatly improved if the TLC operates in a $\gamma\gamma$ mode.
[d] Estimated from work on charged Higgs detection (via $gb \to tH^- \to t\bar{t}b$) for $\tan\beta \simeq 1$, $m_t = 180$ GeV, 100 fb^{-1} integrated luminosity and assuming a b-tagging efficiency $\epsilon_b = 0.3$ [72].
[e] ALEPH and DELPHI limit [66], while the OPAL limit [73] is $M(P^{\pm}) > 35\ GeV$. The kinematic limit in LEP I is $M_Z/2$.
[f] Kinematical limits for LEP200 and a 1 TeV e^+e^- collider (TLC) [74].
[g] Contribution to the $\bar{t}t$ cross section in multiscale models [75].
[h] QCD pair production of colored PGBs with decay into 4 jets [76].
[i] QCD pair production of colored PGBs, each decaying to $t\bar{t}$, $t\bar{b}$, $t\tau$ or $t\nu_\tau$ should allow higher reach in mass. This has yet to be studied.

4 Oblique corrections and parameters S through X

Although the investigations about the new physics beyond the SM has been continued for many years, no any new particles beyond those predicted by the SM (such as the Z and W gauge bosons and the top quark) have been discovered by various experiments. If the new physics is too heavy to be directly produced in current experiments, there are generally two ways for it to indirectly contribute. It can contribute to:

> *(a). the propagation of the gauge bosons (γ, Z^0 and $W^{\pm}$),* e.g., *the so-called "Oblique" corrections;*
>
> *(b). the three point fermion-boson and/or the four point fermion-fermion interactions,* e.g., *the "Non-oblique" corrections;*

In this section we present a brief review for the definitions and estimations of the six oblique parameters S through X.

4.1 Oblique parameters (S, T, U, V, W, X)

In general, if only the "oblique" contributions from new physics are considered, one can write the self-energy functions of gauge bosons as a summation of the SM part and the new physics part:

$$\Pi_{ab}(q^2) = \Pi_{ab}^{SM}(q^2) + \delta\Pi_{ab}(q^2), \quad with \quad (a,\ b) = (ZZ,\ WW,\ \gamma\gamma,\ Z\gamma), \tag{25}$$

where the first term represents the SM contributions, while all new-physics "oblique" corrections are contained in the second term.

The oblique corrections have been very conveniently parametrized in terms of three parameters S, T and U (the U parameter is small and usually can be ignored) by Peskin and Takeuchi [10]. They assumed that the new particles running round the loops have large masses (much larger than the masses of the W and Z^0) so that the self-energies could be described well by a Taylor expansion to linear order: $\delta\Pi_{ab} \approx A_{ab} + B_{ab}q^2$, the errors of order (M_Z^2/M_{new}^2) were neglected.

Under this approximation Peskin and Takeuchi [10] estimated S in TC theory from a scaled-up QCD dispersion relation and concluded that $S \approx 1.6$ for the OGTM and $S \approx 0.5$ for the

ODTM (assuming $N_{TC} = 4$ in both cases), while the fitting of the data (done at 1991) predicted $S = -1.52 \pm 0.84$ [10]. But the situation has been changed recently, a new fit (done at 1994) of the electroweak data leads to $S = -0.21 \pm 0.24^{-0.06}_{+0.17}$ [35], which is close to zero with small error, and the tendency to find $S < 0$ that existed in earlier data is no longer present.

Burgess *et al* [12] extended the (S, T, U) parametrization by introducing three additional parameters (V, W, X) to describe the lowest non-trivial momentum dependence in oblique diagrams. If the heavy new physics assumption is dropped, the gauge-boson self-energies have some complicated dependence on q^2 that cannot be adequately expressed using the first few terms of a Taylor expansion. Nonetheless, since precision observables are associated only with the scales $q^2 \approx 0$, $q^2 = M_Z^2$ or $q^2 = M_W^2$, it turns out that it is possible in practice to parametrize oblique effects due to light new physics in terms of only six parameters S, T, U, V, W and X. These are defined as [12, 13, 14]

$$\begin{aligned}
\alpha S &= -4 s_w c_w (c_w^2 - s_w^2) \delta\widehat{\Pi}_{ZA}(0) - 4 s_w^2 c_w^2 \delta\widehat{\Pi}_{AA}(0) \\
&\quad + 4 s_w^2 c_w^2 \left[\frac{\delta\Pi_{ZZ}(M_Z^2) - \delta\Pi_{ZZ}(0)}{M_Z^2} \right], \qquad (26) \\
\alpha T &= \frac{\delta\Pi_{WW}(0)}{M_W^2} - \frac{\delta\Pi_{ZZ}(0)}{M_Z^2} \qquad (27) \\
\alpha U &= 4 s_w^2 \left[\frac{\delta\Pi_{WW}(M_W^2) - \delta\Pi_{WW}(0)}{M_W^2} \right] - 4 s_w^2 c_w^2 \left[\frac{\delta\Pi_{ZZ}(M_Z^2) - \delta\Pi_{ZZ}(0)}{M_Z^2} \right] \\
&\quad - 4 s_w^4 \delta\widehat{\Pi}_{AA}(0) - 8 c_w s_w^3 \delta\widehat{\Pi}_{ZA}(0), \qquad (28) \\
\alpha V &= \delta\Pi'_{ZZ}(M_Z^2) - \left[\frac{\delta\Pi_{ZZ}(M_Z^2) - \delta\Pi_{ZZ}(0)}{M_Z^2} \right], \qquad (29) \\
\alpha W &= \delta\Pi'_{WW}(M_W^2) - \left[\frac{\delta\Pi_{WW}(M_W^2) - \delta\Pi_{WW}(0)}{M_W^2} \right], \qquad (30) \\
\alpha X &= -s_w c_w \left[\delta\widehat{\Pi}_{ZA}(M_Z^2) - \delta\widehat{\Pi}_{ZA}(0) \right], \qquad (31)
\end{aligned}$$

where $\delta\widehat{\Pi}(q^2) \equiv \delta\Pi(q^2)/q^2$, and where $\delta\Pi'(q^2)$ denotes the ordinary derivative with respect to q^2. The V, W and X are intentionally defined so that they vanish when the self-energies are linear functions of q^2 only, in which case the STU parametrization is exactly recovered. For the questions of how the above parameters appear in expressions for Z-pole observables, the reader can see the refs.[12, 13, 14, 25].

A global fit (done at the end of 1993) to the data in which all six oblique parameters S through X are allowed to vary simultaneously gives the one standard deviation bounds [14]:

$$\begin{aligned}
S &\sim -0.93 \pm 1.7, \quad V \sim 0.47 \pm 1.0, \\
T &\sim -0.67 \pm 0.92, \quad W \sim 1.2 \pm 7.0, \qquad (32) \\
U &\sim -0.60 \pm 1.1, \quad X \sim 0.1 \pm 0.58.
\end{aligned}$$

From eq.(32), it is easy to see that the inclusion of V, W, and X weakens the bounds on S, T, and U considerably. This analysis raises the possibility that a TC model with new light particles with masses of order M_Z may be experimentally viable. There are two possible sources of such light particles: light technifermions and the light PGBs that occur in many TC models with large global symmetries. In ref.[13], N.Evans estimated the possible contributions to parameters V, W, and X from the light technifermions and pseudo-Goldstone bosons. For the OGTM, the inclusion of new contributions could relax the upper bounds on S and T by between 0.1 and 1

depending upon the precise particle spectrum. For more details the reader can see the original paper [13].

In ref.[77], the authors argue that the oblique corrections to all Z-pole observables can be expressed in terms of only two parameters, S' and T', which are linear combinations of S through X:

$$S' = S + 4(c_w^2 - s_w^2)X + 4s_w^2 c_w^2 V, \tag{33}$$

$$T' = T + V \tag{34}$$

The effective vertex for neutral currents at the Z-pole is now given by

$$\begin{aligned} i\Lambda^\mu_{\rm nc}(M_Z^2) &= -i\,\frac{e}{s_w c_w}\,(1+\frac{1}{2}\alpha T')\,\gamma^\mu \cdot \\ &\quad \left[I_3^f\gamma_L - Q^f\left(s_w^2 + \frac{\alpha S'}{4(c_w^2-s_w^2)} - \frac{c_w^2 s_w^2\,\alpha T'}{c_w^2 - s_w^2}\right)\right]. \end{aligned} \tag{35}$$

So, in confronting some model of light new physics with Z-pole data, one would calculate S' and T' rather than S and T. With S' and T' defined this way, the low-energy neutral-current observables now depend on S', T', V, and X; the W-mass depends on S', T', U, V, and X. Fits to the most recent LEP and SLC data (Winter 1995) are presented in [27], the result is

$$\begin{aligned} S' &= -0.20 \pm 0.20, \quad T' = -0.13 \pm 0.22 \\ \alpha_{\rm s}(M_Z) &= 0.127 \pm 0.005 \end{aligned} \tag{36}$$

4.2 Estimations of S through X in the OGTM

Generally speaking, the contributions to the parameters S through X (in most cases only S was considered) in the OGTM can be divided into two parts: the 'high-energy' part from the techniquarks and technileptons, and the 'low-energy' part from those PGBs. It is well known that, only a few years ago, oblique correction considerations hinging on the parameter S tended to rule out certain models of Technicolor [10, 24].

The S-argument against Technicolor was countered in ref.[78], where it was pointed out that the high-energy contribution determined from scaling the parameters of the QCD chiral lagrangian represents an upper bound, and that other methods used to estimate this contribution result in a smaller or negative value for the high-energy piece. The authors of ref.[78] stated that the isospin splitting and techniquark-technilepton splitting in the OGTM can reduce the predicted value of the electroweak parameter S, without making a large contribution to the T parameter. they naively estimate the high-energy contribution by calculating the one loop technifermion diagrams, and find that, after adding it to the low-energy piece, the S-argument against Technicolor can be invalidated. Thus, ref. [78], entitled "Revenge of the one-family Technicolor models," re-established the possible phenomenological viability of this model.

In ref.[79], the authors examined the oblique correction phenomenology of one-family technicolor model with light pseudo-Goldstone bosons. From loop calculations based on a gauged chiral lagrangian for Technicolor, they conclude that even though loops with light Goldstone bosons give a negative contribution to S measured at the Z-pole, this effect is not sufficiently large to unambiguously counter the 'S-argument' against one-family Technicolor.

Using the effective lagrangian method, the authors [79] explicitly calculated the one-loop oblique corrections to electroweak parameters form different sources. We here only list the main results presented in ref.[79], for more details the reader can see the original paper.

- The "high-energy" contribution is large and positive:

$$S(\Lambda_{TC}) = -16\pi \frac{N_d N_{TC}}{N_{QCD}} L_{10}^{QCD}(\Lambda_{QCD}) \sim +1. \tag{37}$$

- The contribution from Isotriplet PGBs is positive in sign, and its size depends on the details of particle spectrum:

$$\alpha S(isotriplets) = \frac{e^2}{24\pi^2} \log \frac{\Lambda_{TC}^2}{M_Z^2} + \text{convergent pieces} \tag{38}$$

- According to the calculations carried out in ref.[79], the contribution to the S parameter from the non-self-conjugate isosinglets is generally negative, and there is no contribution from a self-conjugate isosinglet. For $m_\pi = M_Z/2$, one has

$$\alpha S = -\frac{e^2 s_w^4 y^2}{2\pi^2} \left(\frac{1}{9}\right), \tag{39}$$

and for $m_\pi \gg M_Z$, one has

$$\alpha S = -\frac{e^2 s_w^4 y^2}{2\pi^2} \left(\frac{1}{60} \frac{M_Z^2}{m_\pi^2}\right). \tag{40}$$

This negative value could be taken as a reassuring sign if one wanted to further establish the phenomenological feasibility of Technicolor. However, it must be appreciated that of the 60 physical PGBs in one-family Technicolor, only three pairs of particles are non-self-conjugate singlets as illustrated in Table 2. The great majority of the PGBs are arranged in triplets, and therefore the negative S contributions from the few non-self-conjugate singlets cannot effectively counter the positive contributions from the many triplets. However, there are ways out. If the isotriplets are heavy as predicted in ref.[49] their positive contribution to S should be very small. While the negative contributions to S from those light isosinglet PGBs may be large in size as given in eq.(39) if the isosinglets of PGBs are sufficiently light. Under these circumstances the negative corrections from light isotriplets would dominate.

In my opinion whether the "S argument" against Technicolor can be avoided or not is still unclear, and therefore, further investigations about this problem are still needed.

5 Non-oblique corrections on $Zb\bar{b}$ vertex in TC models

Now we turn to study the non-oblique corrections to the physical observables in TC models [8, 7]. Of cause, other new physics models also can contribute to the observables in different ways, such as corrections from the mirror particles in the Minimal Supersymmetric Standard Model(MSSM) [80] or other beyond models [81], but we here don't deal with such models.

In the process of ETC gauge group breaking, many ETC gauge bosons become massive. Some of them called "sideways" cause the transition of the ordinary fermions to the technifermions, some of them called "horizontal" connect the ordinary fermions themselves, and the others called "diagonal" diagonally interact with both the ordinary fermions and technifermions.

There are two kinds of sources of non-oblique corrections to the $Zb\bar{b}$ vertex in non minimal TC models, namely from ETC gauge boson exchange [17, 19, 20] and from charged PGB exchange [22, 23], and we will discuss these two kinds of corrections in the following subsections, respectively.

5.1 Negative contributions from sideways ETC boson exchange

In ref.[17] R.S.Chivukula *et al* have estimated the non-oblique effects in the $Zb\overline{b}$ vertex from sideways ETC gauge boson exchanges. If the top quark mass is generated by the exchange of an $SU(2)_W$ neutral ETC gauge boson (the most popular case for ETC models) with mass M_{ETC}, then this gauge boson carries technicolor and couples with strength g_{ETC} to the current

$$\xi\,\overline{\Psi}^i_L\,\gamma^\mu\,T^{iw}_L + (\frac{1}{\xi})\,\overline{t}_R\,\gamma^\mu\,U^w_R, \tag{41}$$

where $\overline{\Psi}_L = (t,b)_L$, $T_L = (U,D)_L$ with U and D technifermions, the indices i and w are for $SU(2)_W$ and technicolor, respectively. The constant ξ is the *Clebsch-Gordon*-like coefficient of order one associated with the ETC gauge group. The top mass is then given by

$$m_t = \frac{g^2_{ETC}}{M^2_{ETC}} < \overline{U}U > \approx \frac{g^2_{ETC}}{M^2_{ETC}} \cdot 4\pi F^2_\pi \tag{42}$$

where the condensate, $< \overline{U}U >$, has been estimated by naive dimension arguments [82] in terms of the technipion decay constant, $F_\pi = 246/\sqrt{N_D}$ with N_D is the number of technifermion doublets.

As described in ref.[17] the ETC interactions in eq.(41) can give rise to a correction

$$\delta g_L = -\frac{\xi^2}{2}\frac{g^2_{ETC}F^2_\pi}{M^2_{ETC}}\frac{eI_3}{s_w c_w} \tag{43}$$

to the tree-level $Zb\overline{b}$ coupling g_L. Substituting for g^2_{ETC}/M^2_{ETC} form eq.(42) one finds

$$\delta g^{ETC}_L \sim \frac{1}{4}\cdot\frac{m_t}{4\pi F_\pi}\cdot\frac{e}{s_w c_w}. \tag{44}$$

This correction δg_L can result in a contribution to the $Zb\overline{b}$ vertex, as given in ref.[17],

$$\Delta^{ETC}_b\ (sideways) \approx -6.6\% \times \xi^2 \cdot \left[\frac{m_t}{180GeV}\right]. \tag{45}$$

For the ODTM, no Pseudo-Goldstone bosons can be survived when the chiral symmetry was broken by the condensate $< T\overline{T} > \neq 0$, but the sideways ETC gauge boson exchange can produce typically large and negative contribution as illustrated in eq.(45). Although the ODTM is only a toy model in nature the correction in eq.(45) is universal for most popular TC/ETC models with standard ETC dynamics(*e.g.* the ETC gauge boson is $SU(2)_W$ singlet).

5.2 Positive contributions from diagonal ETC boson exchange

The sideways ETC gauge bosons must exist in the realistic model to generate the quark and lepton masses, while the existence of diagonal ETC gauge bosons is model-dependent. Lightest ETC bosons are the sideways and diagonal ETC gauge bosons associated with the top quark.

In ref.[19] Kitazawa calculated the radiative contributions to the $Zb\overline{b}$ vertex generated by the diagonal ETC gauge boson exchange. He found that the diagonal ETC gauge boson also yields non-oblique correction through the mixing with Z boson, and both kinds of contributions (sideways and diagonal) are *positive* and don't cancel each other. The diagonal contribution is 30% of the sideways contribution when $\xi_t = 1$.

Very recently, Wu [20] reconsidered the non-oblique corrections on the $Zb\overline{b}$ vertex from diagonal ETC gauge boson exchange. He found that the diagonal ETC gauge boson exchange really contribute to the $Zb\overline{b}$ vertex as calculated by Kitazawa, but the contributions from the sideways and diagonal ETC gauge boson exchanges are *opposite in sign* , and therefore, *these two kinds of contributions will cancel each other.*

According to the calculations in ref.[20], for one-generation TC model the diagonal ETC gauge boson exchange could result in a contribution the tree-level $Zb\overline{b}$ coupling [20]:

$$\delta g_L^b(diagonal) \approx -\frac{f_Q^2}{8m_{X_D}^2}\frac{N_C}{N_{TC}+1}\, g_{E,L}\, (g_{E,R}^U - g_{E,R}^D), \tag{46}$$

where the $N_C = 3$ is the number of colors, the N_{TC} is the number of technicolors, and the definitions of all other parameters appeared in above equation can be found in ref.[20]. The result of eq.(46) differs by a minus sign from the loop estimate of ref.[83]. Summing up the sideways and diagonal ETC exchange contributions gives:

$$\delta g_{L,ETC}^b \approx -\frac{f_Q^2}{8}\left[\frac{g_{E,L}^U\,(g_{E,L}^U - g_{E,L}^D)}{m_{X_D}^2}\frac{N_C}{N_{TC}+1} - \frac{g_{E,L}^2}{m_{X_S}^2}\right]. \tag{47}$$

It is seen from the above expression that the two contributions are of comparable magnitude but with opposite sign, and they will basically be canceled out for proper choice of parameters. It is also possible for ETC exchange to give a small positive correction to R_b.

Obviously, because of the cancellation of these two kinds of contributions, the ETC-corrected R_b value could lie in a range consistent with the LEP data *if there were no other kinds of corrections on this ratio.* Although there are some differences between the one-generation TC model studied in ref.[20] and the QCD-like OGTM, the basic structures (such as the gauge group of the model, the particle spectrum, the couplings, $\cdots$, etc) are very similar. And therefore we can assume that the diagonal ETC gauge boson exchange in the ordinary OGTM may produce the similar positive contributions to the R_b, at least the total ETC non-oblique correction is very small.

We know that, however, besides the "high energy" contributions to the $Zb\overline{b}$ vertex from ETC gauge boson exchanges, there are also "low-energy" negative contributions from the charged PGBs as estimated in ref.[22, 23]. These contributions will decrease the ratio R_b by as large as a few percent [22], and the exact size of corrections from charged PGBs depend on the top quark mass and the masses of charge PGBs (color singlets and color octets). In spite of some uncertainties in the evaluation of ref.[20], Wu's work is great help for one to extract the lower-limit on the charged PGBs from the present data because one can now reasonably assume that the total corrections on the ratio R_b from ETC dynamics are very small and can therefore be neglected at first approximation, *e.g.*, one can assume that:

$$\begin{aligned} \Delta_b^{new}(OGTM) &= \Delta_b^{ETC}(sideways) + \Delta_b^{ETC}(diagonal) + \Delta_{bv}^{P^\pm} + \Delta_{bv}^{P_8^\pm} \\ &\approx \Delta_{bv}^{P^\pm} + \Delta_{bv}^{P_8^\pm}. \end{aligned} \tag{48}$$

5.3 Negative contributions from charged PGBs

In contrast to the ODTM (where there is no PGBs), the charged PGBs appeared in the OGTM also contribute a negative correction to the $Zb\overline{b}$ vertex as estimated in refs.[22, 23]. In short, there are three kinds of non-oblique corrections on the $Zb\overline{b}$ vertex in the OGTM:

(a). $\Delta_b^{(top)}$, the correction on the $Zb\overline{b}$ vertex arising from loop diagrams involving the internal heavy top quark, which is the same as in the standard model;

(b). Δ_b^{ETC}, the correction on the $Zb\overline{b}$ vertex from sideways and diagonal ETC gauge boson exchange in the OGTM, the total corrections is small and can be neglected at first approximation;

(c). $\Delta_b(PGBs) = \Delta_{bv}^{P^\pm} + \Delta_{bv}^{P_8^\pm}$, the corrections on $Zb\overline{b}$ from the color singlet and color octet charged PGBs.

In ref.[22, 23] we calculated the non-oblique corrections to the $Zb\overline{b}$ vertex from the charged PGBs and obtained the lower limits on the color octet PGBs. We here just discuss this work briefly.

The gauge couplings of the PGBs to the gauge bosons ($\gamma,\ Z,\ W^\pm$) are determined by their quantum numbers. The coupling of PGBs to ordinary fermions are induced by ETC interactions and hence are model dependent. However, these couplings are generally proportional to the fermion masses. In ref.[59] J.Ellis *et al* estimated the Yukawa couplings to ordinary fermions of the PGBs in the OGTM under some simplifying assumptions. In their first Monophagic Model, the ETC generators commute with $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ and couple each type of ordinary fermions to the same type of technifermions in the sense of avoiding the FCNC problem. The effective Yukawa couplings of the charged color singlet(color octets) PGBs $P^\pm$($P_8^\pm$) are the form of

$$\left(\frac{-i}{F_\pi}\right) P^+ \left[\overline{u}\,(V_{km}\,m^d\,\frac{1+\gamma_5}{2} - m^u\,V_{km}\,\frac{1-\gamma_5}{2})\,d\sqrt{\frac{2}{3}}\right] + H.C. \tag{49}$$

$$\left(\frac{-i}{F_\pi}\right) P_{8\alpha}^+ \left[\overline{u}\,(V_{km}\,m^d\,\frac{1+\gamma_5}{2} - m^u\,V_{km}\,\frac{1-\gamma_5}{2})\,\lambda^\alpha\,d\right] 2 + H.C. \tag{50}$$

where the V_{km} is the element of KM matrix. In these two effective couplings the Goldstone boson decay constant F_π is $F_\pi = 246/\sqrt{N_D} = 123\,GeV$ in order to ensure the correct masses for the gauge bosons Z^0 and $W^\pm$.

Based on the effective Yukawa couplings as shown in eqs.(49, 50) and the ZP^+P^- couplings given in ref.[84] we can write down the Feynman rules needed in the calculation for the TC correction to $Zb\overline{b}$ vertex at one-loop order.

$$\begin{aligned}
[\mathbf{Z}-\mathbf{b}-\overline{\mathbf{b}}] &= ie\gamma^\mu(v_b - a_b\gamma_5) && (51)\\
[\mathbf{P}^+-\mathbf{t}-\mathbf{b}] &= i\frac{V_{tb}}{2F_\pi}\cdot\sqrt{\frac{2}{3}}[m_t(1-\gamma_5) - m_b(1+\gamma_5)] && (52)\\
[\mathbf{P_8^+}-\mathbf{t}-\mathbf{b}] &= i\frac{V_{tb}}{2F_\pi}\cdot 2\lambda^\alpha[m_t(1-\gamma_5) - m_b(1+\gamma_5)] && (53)\\
[\mathbf{Z}-\mathbf{P}^+-\mathbf{P}^-] &= ie\frac{1-2s_w^2}{2s_wc_w}(P^+-P^-)^\mu && (54)\\
[\mathbf{Z}-\mathbf{P_8^+}-\mathbf{P_8^-}] &= ie\frac{1-2s_w^2}{2s_wc_w}(P^+-P^-)^\mu\cdot\delta_{\alpha\beta} && (55)
\end{aligned}$$

where the λ^α are the Gell-Mann $SU(3)_c$ matrices and the vector and axial vector coupling constants for bottom quark are:

$$v_b = \frac{-\frac{1}{2}+\frac{2}{3}s_w^2}{2s_wc_w},\quad a_b = \frac{-1}{4s_wc_w} \tag{56}$$

After the analytical calculation of those relevant Feynman diagrams as shown in Fig.1 of ref.[22] we got an effective $Zb\bar{b}$ vertex:

$$\begin{aligned} & ie\gamma^{\mu}(v_b - a_b\gamma_5) + ie\gamma^{\mu}(1-\gamma_5)\frac{A^2}{16\pi^2}\cdot |V_{tb}|^2 \\ & \cdot\{\ [F_{1a}+F_{1b}+F_{1c}\,] + [F_{8a}+F_{8b}+F_{8c}]\cdot 6\lambda^{\alpha}\lambda^{\alpha}\ \}. \end{aligned} \tag{57}$$

The explicit expressions of the form factors F_{1a}, F_{1b}, F_{1c} and F_{8a}, F_{8b}, F_{8c} can be found in ref.[22].

Using the effective $Zb\bar{b}$ vertex as given in eq.(57), it is straightforward to calculate the contributions to the partial width Γ_b and R_b from the charged PGBs. We get the results:

$$\delta\Gamma_{TC} = \Gamma_b^{(0)}[\Delta_{bv}^{P^{\pm}} + \Delta_{bv}^{P_8^{\pm}}] \tag{58}$$

where $\Gamma_b^{(0)} = 380\ MeV$, and the vertex factors are the form of

$$\begin{aligned} \Delta_{bv}^{P^{\pm}} &= \frac{A^2 s_w c_w}{4\pi^2}\,|V_{tb}|^2\frac{(3+\beta^2)(v-1)+3(1-\beta^2)(v+1)}{(3-\beta^2)v^2+2\beta^2} \\ &\quad \cdot [\,ReF_{1a}+ReF_{1b}+ReF_{1c}\,], \end{aligned} \tag{59}$$

$$\begin{aligned} \Delta_{bv}^{P_8^{\pm}} &= \frac{6\,A^2 s_w c_w}{4\pi^2}\,|V_{tb}|^2\,T(8)\cdot\frac{(3+\beta^2)(v-1)+3(1-\beta^2)(v+1)}{(3-\beta^2)v^2+2\beta^2} \\ &\quad \cdot [\,ReF_{8a}+ReF_{8b}+ReF_{8c}\,] \end{aligned} \tag{60}$$

where the s_w and c_w are the mixing angle, and the explicit expressions of all other parameters in eqs.(59, 60) can be found in ref.[22].

5.4 Updated constraints on masses of PGBs

As described in ref.[22], the magnitude of the vertex factors $\Delta_{bv}^{P^{\pm}}$ and $\Delta_{bv}^{P_8^{\pm}}$ depends on three parameters: the top quark mass m_t, the mass of color-singlet PGBs m_{p1} and the mass of color-octet PGBs m_{p2}. Therefore, the exact size of this kind of corrections depend on the mass spectrum of top quark and charged PGBs. Historically, theoretical estimations about the masses of charged PGBs have been done by many authors[56, 8]. We here discuss briefly the constraints on the masses of color-singlet charged PGBs $P^{\pm}$ and color-octet charged PGBs $P_8^{\pm}$ because only these two kinds of PGBs can contribute significantly to the $Zb\bar{b}$ vertex.

Using the SIP, it is straightforward to calculate the values of $\Delta_{bv}^{P^{\pm}}$ and $\Delta_{bv}^{P_8^{\pm}}$ from eqs.(59, 60). For $m_t = 180\ GeV$,

$$\Delta_{bv}^{P^{\pm}} = (-0.013 \sim -0.002),\ \text{for}\ m_{p1} = 50 - 400\ GeV, \tag{61}$$

$$\Delta_{bv}^{P_8^{\pm}} = (-0.050 \sim -0.003),\ \text{for}\ m_{p2} = 200 - 650\ GeV. \tag{62}$$

The contributions from the charged PGBs are always negative and will push the OGTM prediction for the vertex factor Δ_b^{new} away from the measured $\Delta_{b,exp}^{new}$. These negative corrections are clearly disfavored by the current data. But fortunately, the charged PGBs show a clear decoupling behavior as listed in eqs.(61, 62).

In the OGTM, the total size of vertex factor Δ_b generally depend on two " free" parameters, the masses m_{p1} and m_{p2} if we use $m_t = 180 \pm 12$ GeV as input. The current data will enable us to exclude large part of parameter space of m_{p1} and m_{p2} in the $m_{p1} - m_{p2}$ plan, as shown in Fig.2. From Fig.2 one can read out the bounds on the masses m_{p1} and m_{p2},

$$m_{p1} > 200\ GeV, \quad \text{for "free"} \quad m_{p2}, \tag{63}$$

and

$$m_{p2} > 600\ GeV, \quad \text{for } m_{p1} \leq 400\ GeV. \tag{64}$$

while the uncertainties of m_t, $\delta m_t = 12\ GeV$, almost don't affect the constraints. The lower limit on m_{p1} as given in eq.(63) is the highest lower limit derived so far from the precision data. The lower limit on m_{p2} in eq.64) is much stronger than that has been given before in ref.[23]. The inclusion of the remained corrections from ETC dynamics in the OGTM will alter (strengthen or waken) the bounds on m_{p1} and m_{p2}, but this ETC effect will be small and model-dependent.

According to our studies we can conclude that the charged PGBs should be much heavier than that estimated before and these heavy charged PGBs most probably decouple from the "low-energy" (e.g., the M_Z scale) physics, if they were existed indeed.

Of cause, the lower limits on charged PGBs depend on the effective couplings of the model being studied. For non-QCD-like TC models, the effective couplings may be different from those as given in ref.[59, 84], and consequently the lower limits may be changed for those models. But I think, the lower limits given here at least can be viewed as a naive estimation for the masses of Charged PGBs appeared even in more realistic TC models.

5.5 Non-Oblique Corrections on some processes from PGBs

Except the non-oblique corrections on the $Zb\bar{b}$ vertex as discussed in previous subsections, the PGBs in TC models also contribute to other physical processes, such as the top quark rare decay, the high-energy neutral current productions of $t\bar{t}$ of $b\bar{b}$ pairs, $\cdots$, etc. In this section we will give a brief review about the relevant works.

- **Top quark rare decays**

The top quark rare decay $t \to cV$ has been studied by several groups in different theories [85, 86, 87]. In ref.[85], we calculated the vertex corrections to the top quark rare decays, such as $t \to cV$ and $t \to cP^0$ (where the V represents the photon γ, QCD gluons g, and gauge boson Z^0), from the PGBs appeared in the OGTM. We found that these new contributions from the PGBs could enhance the SM branching ratios by as much as $3 \sim 4$ orders of magnitude for the favorable parameter space, as illustrated in Table 4. For more details please see the original paper [85].

Table 4: The maximum branching ratios of top quark rare decays predicted by different models

	SM [86]	2HDM [86]	QCD[87]	Charginos[87]	PGBs[85]
$Br(t \to cZ)$	10^{-12}	10^{-9}	10^{-9}	10^{-8}	10^{-7}
$Br(t \to c\gamma)$	10^{-12}	10^{-8}	10^{-8}	10^{-8}	10^{-8}
$Br(t \to cZ)$	10^{-10}	10^{-6}	10^{-6}	10^{-7}	10^{-6}
$Br(t \to cP^0)$					10^{-9}

- **The rare decays of $Z \to b\bar{s}(\bar{b}s)$**

One of the most characteristic predictions of the SM is the very small magnitude of FCNC processes. Consequently, decays induced by FCNC are an effective way to test the SM, and, in particular, provide a potentially very sensitive probe of physics beyond the SM. Experimentally, the e^+e^- machines can be used as Z factories providing an opportunity to examine the decay

properties of the neutral weak gauge boson in detail. The current experimental limit on the FCNC rare Z-decay is about 10^{-5} [89]. The dominant mode of the flavor changing Z-decays is $Z \to b\overline{s}(\overline{b}s)$, and such rare decay has been thoroughly studied in the SM [90], two-Higgs doublet model [91] and in the MSSM [92]. The studies show, in most case, the contributions of these models to $Br(Z \to b\overline{s} + \overline{b}s)$ are at the order of 10^{-7}. Such contributions are too small to be detected in near future.

In Ref.[59], two kinds of the OGTM have been studied by Ellis *et al*: (a). Model I, the ETC generators commute with $SU_L(2) \otimes U_Y(1) \otimes SU(3)_c$ and couple each ordinary fermion to the technifermion of the same type; (b). Model II, the ETC/TC generators have $SU(2)_L$ isospin=0 but couple u,c,t...to $\overline{E}$, d,s,b...e,μ, τ... to $\overline{U}$ and ν_e, ν_μ, ν_τ... to $\overline{D}$). The flavor-changing decay $Z \to b\overline{s}(\overline{b}s)$ induced through PGBs is calculated in these two kinds of models in ref.[88].

Generally speaking, the corrections from the color octet PGBs is much larger than those coming from the color singlet PGBs, so that the later one can be neglected.

For Model I, we found that an interesting branching ratio $B(Z \to b\overline{s} + \overline{b}s) \sim 10^{-6}$ can be obtained for particular choices of the parameters, such magnitude of the order of branching ratio is at the border of being detectable.

For Model II, the PGBS contributions can strongly enhance the branching ratio $Br(Z \to b\overline{s} + \overline{b}s)$. With the current experimental limit on the branching ratios of rare Z-decay, the constraints on the mass of color octet Pseudo-Goldstone-bosons can be derived: $m_p > 306\ GeV$ for $m_t = 170\ GeV$ and $m_p > 333\ GeV$ for $m_t = 190\ GeV$ respectively. Consequently, the decay $Z \to b\overline{s}(\overline{b}s)$ may provide a unique window to study the TC theory.

- **Production of top pairs at NLC**

At next generation e^+e^- collider (NLC), operating at the center-of-mass of 500 GeV with a luminosity of order $10^{33} cm^{-2} sec^{-1}$ [93], the top quark is dominantly produced via the process $e^+e^- \to t\overline{t}$. The radiative corrections to this process have been calculated in the SM, in the 2HDM [94] and in the MSSM [95]. In ref.[96] we calculated the TC $0(\alpha m_t^2/m_W^2)$ corrections to this process, which coming from the virtual effects of PGBs.

Taking into account the TC $O(\alpha m_t^2/m_W^2)$ corrections, renormalized amplitude for $e^+e^- \to t\overline{t}$ is given by:

$$M_{ren} = M_0 + \delta M^{(\gamma)} + \delta M^{(Z)} \tag{65}$$

where M_0 is the amplitude at tree level, $\delta M^{(\gamma,Z)}$ represents the TC $O(\alpha m_t^2/m_W^2)$ corrections coming from the effective $\gamma t\overline{t}$ (Z t$\overline{t}$) vertex.

After the analytical calculations for those relevant Feynman diagrams, the renormalized vertices can be expressed in terms of form factors, which only depend on the center-of-mass energy S and some masses. By the numerical calculations we found that the corrections from the color octet PGBs are dominate. The one-loop $O(\alpha m_t^2/m_W^2)$ corrections to the physical observables σ, A_{LR} and to the A_{FB} from color octet PGBs can be rather large for relatively light PGBs. For $m_t = 174\ GeV$ and $m_P = 246\ GeV$, the maximum correction to the observables σ, A_{LR} and A_{FB} can reach -12.3%, -11.8% and -3.3% respectively. For heavier color octet PGBs, the corrections will decrease rapidly(showing a good decoupling behavior). Generally speaking, the corrections to σ, A_{LR} and A_{FB} from Technicolor are relatively larger than the others as presented in ref.[94, 95] and might be observed at NLC, since all the production and decay form factors of the top quark might be measured at the level of a few percent at NLC [93]. If any large new physics signals are received, these virtual effects of colored-PGBs might provide an possible interpretation.

- **Production of bottom pairs above Z-pole**

In ref.[97], we calculated the TC $O(\alpha m_t^2/m_W^2)$ corrections to the process $e^+e^- \to b\bar{b}$ at high energy e^+e^- collider above the Z pole. We found that the corrections from the color octet PGBs dominate. These TC corrections will affect the size of total cross-section $\sigma(e^+e^- \to b\bar{b})$, as well as the forward-backward asymmetry A_{FB} and left-right asymmetry A_{LR},

$$\sigma^{TC} = \sigma_0 + \delta\sigma^{TC}, \quad \delta A_{LR} = A_{LR}^{TC} - A_{LR}^0, \quad \delta A_{FB} = A_{FB}^{TC} - A_{FB}^0 \tag{66}$$

where σ_0, A_{LR}^0 and A_{FB}^0 stand for the values in the Born approximation. While σ^{TC}, A_{LR}^{TC} and A_{FB}^{TC} refer to the values with TC $O(\alpha m_t^2/m_W^2)$ corrections.

For the center-of-mass energy $\sqrt{s}$=500 GeV, $m(P^\pm) = 60\ GeV$, $m(P_8^\pm) = 200 \sim 500$ GeV and $m_t = 175 \pm 10\ GeV$, the numerical values of the TC corrections on the observables σ, A_{FB} and A_{LR} from the charged PGBs are the following:

$$\frac{\delta\sigma^{TC}}{\sigma^0} = [(-1.9\% \sim -1.0\%), (-2.6\% \sim -1.3\%), (-4.2\% \sim -2.6\%)] \tag{67}$$

$$\frac{\delta A_{LR}}{A_{LR}^0} = [(-2.3\% \sim 1.0\%), (-2.2\% \sim 1.3\%), (-1.8\% \sim 1.5\%)] \tag{68}$$

$$\frac{\delta A_{FB}}{A_{FB}^0} = [(-1.4\% \sim 1.0\%), (-1.1\% \sim 1.3\%), (-0.4\% \sim 1.8\%)] \tag{69}$$

From the above results, one can see that the TC correction on the total cross-section $\sigma(e^+e^- \to b\bar{b})$ is relatively large for $m_t \approx 180\ GeV$, this effects may be detectable if the precision of future experiments at NLC could reach 1% level. On the other hand, the corrections to the left-right and forward-backward asymmetries are rather small ($\leq 1\%$) if charged PGBs are heavy as shown in eqs.(63, 64).

- **Corrections on $BR(B \to X_s\gamma)$ from Charged PGBs**

Recently the CLEO collaboration has observed [98] the exclusive radiative decay $B \to K^*\gamma$. The newest upper and lower limits on the branching ratio of $B \to X_s\gamma$ published by CLEO [99] are

$$1.0 \times 10^{-4} < BR(B \to X_s\gamma) < 4.2 \times 10^{-4}, \quad at \quad 95\% C.L \tag{70}$$

respectively. As a loop-induced flavor changing neutral current(FCNC) process the inclusive decay(at quark level) $b \to s\gamma$ is in particular sensitive to contributions from those new physics beyond the Standard Model(SM) [100].

The decay $b \to s\gamma$ has been investigated within the framework of Extended Technicolor(ETC) models by L.Randall and R.S.Sundrum [101]. They concluded that the contributions from the ETC gauge boson exchange are rather small.

In ref.[102], we estimated the possible contributions to the decay $b \to s\gamma$ from the exchanges of the charged PGBs $P^\pm$ and $P_8^\pm$ with an ordinary ETC sector. We find that: the new contribution is negative in sign and the total contribution depends on the values of the masses of the top quark and those charged PGBs.

If we take experimental result $BR(B \to X_c e\overline{\nu}) = 10.8\%$ [44], the branching ratios of $B \to X_s\gamma$ is found to be:

$$BR(B \to X_s\gamma) \simeq 10.8\% \times \frac{6\alpha_{QED}\, |C_7^{eff}(m_b)|^2}{\pi g(m_c/m_b)} \left(1 - \frac{2\alpha_s(m_b)}{3\pi} f(m_c/m_b)\right)^{-1}. \tag{71}$$

where the explicit form of the coefficient $C_7^{eff}(m_b)$ can be found in the original paper [102]. The current $CLEO$ experimental results can eliminate large part of the parameter space in the

$m(P^{\pm}) - m(P_8^{\pm})$ plan, and specifically, one can put a strong lower bound on the masses of color octet charged PGBs $P_8^{\pm}$: $m(P_8^{\pm}) > 400\ GeV$ at $95\% C.L$ for free $m(P^{\pm})$. After we completed this work [102] ref.[103] came to our attention, the author also estimated the Technipion contributions to the rare decay $b \to s\gamma$.

6 Summary and Conclusions

In this report we presented a systematic investigation about the non-oblique corrections on the $Zb\overline{b}$ vertex from the new physics, such as the ETC dynamics and the pseudo-Goldstone bosons. We also discussed the non-oblique corrections on other processes from the PGBs. According the existed studies one can expect that the charged PGBs should much heavier than that estimated ever before.

In my opinion, Technicolor plus extended technicolor is the most ambitious attempt yet to explain the physics of electroweak and flavor symmetry breaking and to do so in natural, dynamical terms. Of cause, TC and ETC theory also encountered many problems as discussed in detail in refs.[24, 104]. It is a difficult task for TC/ETC theory to explain the large top quark mass and at the same time satisfy the constraints from the precision electroweak measurements, such as the limits from the parameters S and Δ_b^{new}. But these difficulties do not dissuade me and others from the TC/ETC philosophy that the origin of this physics is to be found at energies far below the Planck scale.

The precision data provided by LEP, Tevatron and other high energy colliders now examine the SM at the loop level. And the accuracy achieved recently permit us to put some constraints on the existed TC and ETC models, to pin down the parameter space. On the other hand, the great progress in the experiments also encourage the researchers to construct new models with special features, just like the wind blowing through the calm lake and enforce the water surface waving!

In recent years, many new TC/ETC models have been constructed in the sense of avoiding the experimental constraints imposed by the precision electroweak data. We here simply list ten examples:

- In ref.[18], the authors have shown that a slowly running technicolor coupling will affect the size of non-oblique corrections to the $Zb\overline{b}$ vertex from ETC dynamics. Numerically, the "Walking TC" [52] reduces the magnitude of the corrections at about 20% level. Although this decrease is helpful to reduce the discrepancy between the TC models and the current precision data, however, this improvement is not large enough to resolve this problem.

- More recently, Evans[53] points out that the constraints from $Zb\overline{b}$ vertex may be avoided if the ETC scale M_{ETC} can be boosted by strong ETC effects.

- In "Non-commuting" theories (i.e., in which the ETC gauge boson which generates the top quark mass does carry weak SU(2) charge), as noted in refs.[17, 83], the contributions on the $Zb\overline{b}$ vertex come from the physics of top-quark mass generation and from weak gauge boson mixing (the signs of the two effects are opposite)[83], and therefore both the size and the sign of the corrections are model dependent and the overall effect may be small and may even increase the $Zb\overline{b}$ branching ratio.

- In "TopC assisted TC" models[105], potentially low energy top color interactions produce a top-condensate and accommendate a heavy top quark, while technicolor is responsible for producing the W and Z masses. For different options the final result is also different. As illustrated in ref.[105] the TopC schemes can contain significant enhancements of the ratio R_b,

where both the topgluon and the Z' will provide a positive contribution. Chivukula *et al* very recently discussed some problems of this model [106].

- "Low-scale technicolor", proposed by King [107] with a low TC confinement scale $\Lambda_{TC} \sim 50 - 100\ GeV$. Such a low TC scale may give rise to the first hints of technicolor being seen at LEP I and spectacular TC signals at LEP 200 and the Tevatron.

- "Technicolor model with a scaler", constructed by Carone [108] and his collaborators. Although the presence of fundamental scalars seems a retreat from the original motivation of TC, these kinds of models are worth of further investigating.

- "Chiral technicolor", constructed by Terning [109]. In this model the technicolor is not vector-like, but a strongly interacting chiral gauge force. The author proposed a toy model to demonstrate his new ideas. On the positive side, chiral TC models offer a simple way to split the t and b quarks without fine-turning. The ETC contribution to Γ_b can be reduced by (up to) a factor of 4, and the techniqurak contribution to the S parameter can also be reduced.

- "Realistic one-family TC model"[110], proposed by Appelquist and Terning. This is an interesting multiscale Technicolor model. The reader can see the original paper [110].

- In a new paper [111], the authors make a connection between the ETC and the CP-violation problem. The electric dipole moments of the neutron and the electron in technicolor theories are estimated to be as large as $\sim 10^{-26}\ e\ cm$ and $\sim 10^{-29}\ e\ cm$, respectively. They also suggest the potential to observe large CP-violating TC effects in the decay $t \to W^+\ b$. This is a new research area in my opinion.

- In ref.[112], Dobrescu proposed a supersymmetric TC model. In this model, the mass hierarchy between the fermion generations arises naturally. Furthermore, this model predicts the CP asymmetries in B meson decays and in $\Delta S = 1$ transitions to be smaller by two orders of magnitude than the ones predicted in the SM. Incorporating the supersymmetry into TC models is a novel and (perhaps) very brave idea, further studies along this direction needed.

Stop here! we are unable to list all new models proposed recently in this paper. But one can understand from this short list that the TC and ETC theories are now experiencing a somewhat rapid developing period, after 10 years "slow walking".

Unfortunately, at present no "standard" or "realistic" (in its exact meaning) TC/ETC models which could resolve the basic difficulties for the theories of DESB elegantly have been emerged. But many progress have been achieved both in the model construction and in the phenomenological analysis in recent years. I think that we now begin "running" in the right direction, and all these progress are valuable and indispensable for the future success.

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Figure Captions

Fig.1: The SM predictions for the ratio R_b compared with the current LEP data. The lower curve with solid triangle symbols is the R_b in SM at one-loop level, while the upper line with solid square symbols represents the R_b with the inclusion of two-loop $0(\alpha\alpha_s)$ QCD contributions. The upper error band corresponds to the current data $R_b = 0.2204 \pm 0.0020$. The lower error bar shows the current experimental measurement of m_t: $m_t = 180 \pm 12\, GeV$.

Fig.2: The constraints on the masses of the charged PGBs in the QCD-like one-generation TC model for $m_t = 180\, GeV$. For more details see the text.